



Effect of fuel blend composition on the efficiency of hydrogen-rich gas production in co-gasification of coal and biomass



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HIGHLIGHTS

- Steam co-gasification of coal and biomass for efficient hydrogen generation.
- Synergy effects: increase in total gas and hydrogen yields.
- Potential influence of biomass ash components in steam co-gasification.

ARTICLE INFO

Article history:

Received 23 December 2013
Received in revised form 17 March 2014
Accepted 18 March 2014
Available online 31 March 2014

Keywords:

Co-gasification
Hydrogen
Synergy
Coal
Biomass

ABSTRACT

Energy generation is predominantly based on fossil fuels. This is related to their high energy density and abundance of resources, as well as market availability and maturity of conversion technologies. Increasing awareness of environmental concerns reflected in relevant regulations regarding the allowable levels of emission of contaminants in energy sector on the one hand, and increasing energy demand on the other impose, however; the need for development of more environment friendly energy technologies and wider utilization of renewable energy resources. Since the latter still faces technological and efficiency problems reflected in unsatisfactory economic characteristics, the efforts could be made to combine the advantages of stable supplies of coal, availability of market-ready, highly efficient and environment friendly gasification technology and utilization of renewable energy resources, biomass. Production of hydrogen as a prospective, environment friendly energy carrier in the process of co-gasification make this option even more attractive, especially if some synergy effects could be observed. In the paper the experimental results proving the influence of a fuel blend composition, in terms of biomass type and content, and process temperature on the total gas volume, gas composition, carbon conversion rate and process efficiency are presented. Synergy effects were reported in co-gasification of coal and biomass of selected energy crops under operating conditions adopted, including increase in the total gas and hydrogen yields when compared to the values observed in coal and biomass gasification. A correlation between ash composition and the synergy effects was also stated. The energy crops types and steam co-gasification operating parameters optimal in terms of hydrogen-rich gas production were also determined.

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1. Introduction

Market limitations affecting supplies of two basic fossil fuels, crude oil and natural gas, as well as the environmental concerns related to the processing of coal in energy sector are the main driving forces of the development of so called clean coal technologies and support given to the activities aiming at increasing the share of renewable energy resources in the energy balance. Gasification, as an alternative to combustion, offers increased efficiency, lower negative environmental impact and wider application range of

the main product – synthesis gas – in power generation and chemical synthesis. It is also considered as one of the most viable options for hydrogen production, as an environment friendly energy carrier [1–3]. Coal gasification applied in Integrated Gasification Combined Cycle offers lower environmental impact, when compared to conventional power generation systems based on natural gas, and higher efficiency than supercritical pulverized coal boilers and steam turbines, by combining production of heat and power, and even hydrogen with carbon dioxide capture [4,5]. There is an increasing trend in the share of electricity generation and coal application as a fuel in the worldwide gasification capacities [6]. Biomass is also considered as a fuel for gasification systems. However, the locally limited resources of biomass, low energy density

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and operational problems related to its physical properties and chemical composition make its application still economically uncompetitive. Most of the present-day gasification reactors dedicated for fossil fuels utilization is unsuitable for biomass processing because of its high content of alkali and alkali earth metals, and relatively high amount of tars released in the process [7–9]. The downdraft moving bed reactors, most commonly applied in biomass processing, produce gas of the lowest particulates and tars content of 0.1–0.2 and 0.1–1.2 g/Nm³ [10], respectively, but are unsuitable for processing of high moisture content biomass. The entrained flow gasifiers, operated at the highest temperatures and pressures, give the product gas free of tars, but their usual capacities are too high for locally limited resources of biomass. They also require energy-consuming pretreatment of biomass in torrefaction or fast pyrolysis processes. Biomass gasification in pressurized fluidized bed reactors creates problems with fuel feeders operation. On the other hand, gas generated in atmospheric fluidized bed reactors is more contaminated than from pressurized ones and contains considerable amounts of particulates (2–35 g/Nm³) and tars (1–15 g/Nm³) [10]. All this makes biomass gasification still a niche area with only 0.3% (402 MW_{th}) of synthesis gas generated worldwide [6]. Waste biomass is, however, a significant element of renewable energy balance in many countries and efforts should be made to make its utilization more efficient than it is in conventional combustion systems. Cultivation of energy crops, especially when combined with industrially degraded area reclamation, may be also of interest, since the waste biomass could satisfy only approximately 7.5% of the world energy demand. Biomass derived gas may be combusted to produce electricity in steam turbines or, after treatment, in gas turbines. Nowadays the first option prevails [7]. Catalysts applied in biomass gasification should decompose tars, prove catalytic activity in methane reforming (if synthesis gas is to be the final product) and/or facilitate production of gas of the desired CO/H₂ ratio. Furthermore, they should be resistant to deactivation, when exposed to H₂S, HCl and to sintering, be easily regenerated and cost competitive. The compounds most commonly studied in this respect are: calcined dolomite (MgCO₃·CaCO₃), calcium carbonate (CaCO₃), olivine (including Fe₂SiO₄ and Mg₂SiO₄), limonite (FeOH), hematite (Fe₂O₃), nickel catalysts, alkali metal salts (Li₂CO₃, Cs₂CO₃, CsNO₃, KNO₃, K₂CO₃, K₂SO₄, NaCO₃ and CaSO₄) [11]. When hydrogen-rich gas production is considered the most promising are nickel catalysts [12,13], olivine and dolomite [13–15], compounds of potassium [16,17], calcium and iron [16,18].

In the light of the above the process of co-gasification of coal and biomass may be promising, especially if some synergy effects could be observed, and the advantage of catalytic properties of biomass ash components could be taken. Most of the literature data on co-pyrolysis and co-gasification concerns processing of waste biomass and problems related to the optimization of feeder designs, fuel blends compositions, operating parameters, as well as biomass pre-treatment and application of catalysts in the process [19]. In some of the works published synergy effects in processing of various fuel blends, including blends of coal and biomass, were reported [20–31], but the need for further research studies in these terms is also claimed [19,21]. In the paper the results of the experimental study on the influence of a fuel blend composition, in terms of biomass type and content, and process temperature on the total gas and hydrogen yields, gas composition, carbon conversion rate and process efficiency were presented. Synergy effects in terms of the total gas and hydrogen yields in the process of steam co-gasification of coal and biomass, in a fixed-bed reactor were also identified. This makes the work complementary to the still limited number of reports on hydrogen-rich gas production in the process of co-gasification of coal and biomass [32–37].

2. Methods and materials

2.1. Materials

The fuels tested were provided by M&D Farms Sp. z o.o. in Świerczów, Poland (*Salix Viminalis*, SV), Department of Agricultural Sciences in Zamość of University of Life Sciences in Lublin, Poland (*Andropogon Gerardi*, AG; *Helianthus Tuberosus*, HT; *Sida Hermaphrodita*, SH and *Spartina Pectinata*, SP), plantation in Föhren, Germany (*Miscanthus X Giganteus*, MXG) and Piast coal mine, Bieruń, Poland (coal seam 208, heading 1291, HC). The selection of biomass types was based on the yielding data as well as the specification of soil, land and climatic requirements of energy crops, which could be met in Poland [38–41].

The proximate and ultimate analyses of the tested fuels were performed in the accredited laboratory of the Department of Solid Fuel Quality Assessment of the Central Mining Institute with application of relevant standards, testing procedures and analyzers. These included: automatic thermogravimetric analyzers LECO: TGA 701 or MAC 500 (contents of moisture, ash, volatiles acc. to PN-G-04560:1998 and PN-G-04516:1998), calorimeters LECO: AC-600 and AC-350 (heat of combustion acc. to PN-G-04513:1981), TruSpecCHN analyzer (contents of carbon, hydrogen, nitrogen acc. to PN-G-04571:1998) and TruSpecS analyzer (sulfur acc. to PN-G-04584:2001). Oxygen content was calculated as: 100% – W^a – A^a – C^a – H^a – S^a (PN-G-04510:1991), and fixed carbon as: 100% – W^a – A^a – V^a (PN-G-04516:1998). Ash composition was analyzed in the accredited Laboratory of Solid Waste Analyses of the Department of Environmental Engineering of the Central Mining Institute with application of wavelength dispersive X-ray fluorescence according to PN-EN ISO 12677. The results are given in Table 1.

The composition of coal and biomass differed significantly in terms of fixed carbon, sulfur and ash contents (higher for coal), and volatiles, oxygen and hydrogen contents (higher for biomass) (see Table 1). Coal derived ash was rich in aluminum and iron oxides, and included substantially less alkali and alkali earth metals than biomass ash.

2.2. Test stand

The experimental study on steam co-gasification of coal and biomass was executed with application of a laboratory scale installation of the Laboratory of Advanced Energy Technologies of the Department of Energy Saving and Air Protection, Central Mining Institute (see Fig. 1). The main elements of the test stand are: a fixed bed reactor of a volume of 0.8 L, heated with a resistance furnace, gasification agents supply system, and product gas treatment and measurement system. For further details see [37].

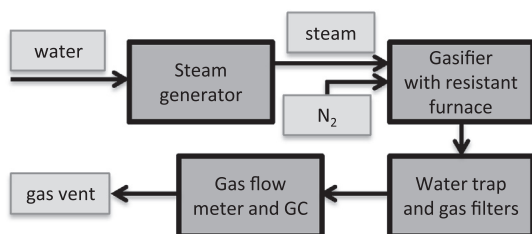
2.3. Methods

Steam co-gasification tests were performed on fuel samples composed of coal and biomass of the total mass of 10 g. Selected fuels were dried, grinded and sieved to the fractions of particle size below 0.2 mm for coal and below 3 mm for biomass. Next, a fuel sample of a biomass content of 0%w/w, 20%w/w, 40%w/w, 60%w/w, 80%w/w or 100%w/w was put into the reactor on a layer of quartz wool, and heated up in nitrogen to the required process temperature of 700, 800 or 900 °C. Then steam as a gasification agent was injected into the reactor with a flow rate of 3.2 mL/min. The selected process variables adopted in the experimental campaign were: process temperature, biomass content in a fuel blend and kinds of fuels tested: steam coal and biomass of selected energy crops: SV, AG, SP, MXG, HT and SH.

Table 1

Proximate and ultimate analyses and ash composition of fuels tested.

Parameter, unit	Fuel						
	SV	AG	HT	SH	MXG	SP	HC
Moisture W ^a , %w/w	4.74	9.72	8.81	8.76	6.78	8.69	6.02
Ash A ^a , %w/w	1.51	3.87	3.18	2.63	1.60	4.31	5.69
Volatiles V ^a , %w/w	73.16	70.26	69.24	71.47	76.00	69.89	31.12
Heat of combustion Q _s ^a , J/g	18,171	16,132	15,989	16,484	16,546	16,920	28,805
Calorific value Q _{cl} ^a , J/g	16,697	14,242	14,543	15,030	14,942	15,481	27,616
Total sulfur S _t ^a , %w/w	0.05	0.06	0.04	0.04	0.05	0.12	0.50
Carbon C _t ^a , %w/w	52.19	53.3	46.62	47.18	53.71	45.77	70.64
Hydrogen H _t ^a , %w/w	6.22	7.57	5.64	5.68	6.59	5.62	4.08
Nitrogen N ^a , %w/w	<LD	<LD	<LD	<LD	<LD	<LD	0.98
Oxygen O ^a , %w/w	35.29	25.54	35.74	35.73	31.27	35.58	13.07
Fixed carbon, %w/w	20.59	16.15	18.77	17.14	15.62	17.11	57.17
SiO ₂ , %w/w							
In ash	14.67	65.18	32.54	3.65	69.01	64.82	46.55
In sample	0.22	2.52	1.03	0.10	1.10	2.79	2.65
Al ₂ O ₃ , %w/w							
In ash	3.18	0.45	1.24	0.64	0.38	0.33	25.65
In sample	0.05	0.02	0.04	0.02	0.01	0.01	1.46
Fe ₂ O ₃ , %w/w							
In ash	0.93	0.28	0.52	0.28	0.19	0.32	8.63
In sample	0.01	0.01	0.02	0.01	0.00	0.01	0.49
CaO, %w/w							
In ash	37.10	11.74	34.20	42.43	15.27	9.99	7.34
In sample	0.56	0.45	1.09	1.12	0.24	0.43	0.42
MgO, %w/w							
In ash	3.46	3.60	2.94	4.66	1.79	1.50	3.82
In sample	0.05	0.14	0.09	0.12	0.03	0.06	0.22
Na ₂ O, %w/w							
In ash	0.53	0.93	1.02	1.75	0.73	1.53	2.60
In sample	0.01	0.04	0.03	0.05	0.01	0.07	0.15
K ₂ O, %w/w							
In ash	22.13	7.26	12.93	21.77	2.98	11.48	1.92
In sample	0.33	0.28	0.41	0.57	0.05	0.49	0.11
SO ₃ , %w/w							
In ash	4.12	3.85	5.90	5.56	4.95	4.95	1.78
In sample	0.06	0.15	0.19	0.15	0.08	0.21	0.10
TiO ₂ , %w/w							
In ash	0.15	0.06	0.08	0.05	0.05	0.05	1.08
In sample	0.00	0.00	0.00	0.00	0.00	0.00	0.06
P ₂ O ₅ , %w/w							
In ash	13.17	5.97	7.87	17.30	3.99	4.45	0.36
In sample	0.20	0.23	0.25	0.45	0.06	0.19	0.02
ZnO, %w/w							
In ash	<LD	<LD	<LD	1.07	<LD	<LD	<LD
In sample	<LD	<LD	<LD	0.03	<LD	<LD	<LD

**Fig. 1.** Schematic of the experimental stand.

Qualitative and quantitative analyses of dry and cooled product gas were performed using a two-channel gas chromatograph Agilent 3000A (GC) and a gas flow meter, respectively. In the gas chromatograph a PLOT U column ($8 \times 10^{-3} \times 0.32 \times 10^{-3}$ m) and analytical column MS5A PLOT ($10 \times 0.32 \times 10^{-3}$ m) with thermal conductivity detectors (TCD) were applied. The PLOT U column with TCD detector was used in determination of carbon dioxide and other compounds of 2–5 carbon atoms in a molecule and the analytical column MS5A with TCD detector for determination of hydrogen, nitrogen, carbon monoxide and methane content in

gas analyzed. The volumes of the main gas components: hydrogen, carbon monoxide, carbon dioxide and methane were calculated as a sum of products of particular gas component concentration, gas flow rate and duration of a time interval for which the concentration and flow rate were determined. A time interval was 192 s for all experiments and resulted from the settings of the chromatographic method. Gas calorific value was calculated as a sum of products of main gas components (hydrogen, carbon monoxide and methane) contents and respective calorific values, according to the standard PN-85/C-04757. Process efficiency was calculated as the ratio of product of gas calorific value and gas volume generated to the product of a fuel calorific value and a fuel mass applied in a test. Carbon conversion rate was calculated as the percentage ratio of carbon content in gasification products to the initial carbon content (fixed carbon, mole) in a sample.

3. Results and discussion

The impact of a fuel blend composition (in terms of biomass type and content), and process temperature on the total gas and hydrogen yields, gas composition, carbon conversion rate and

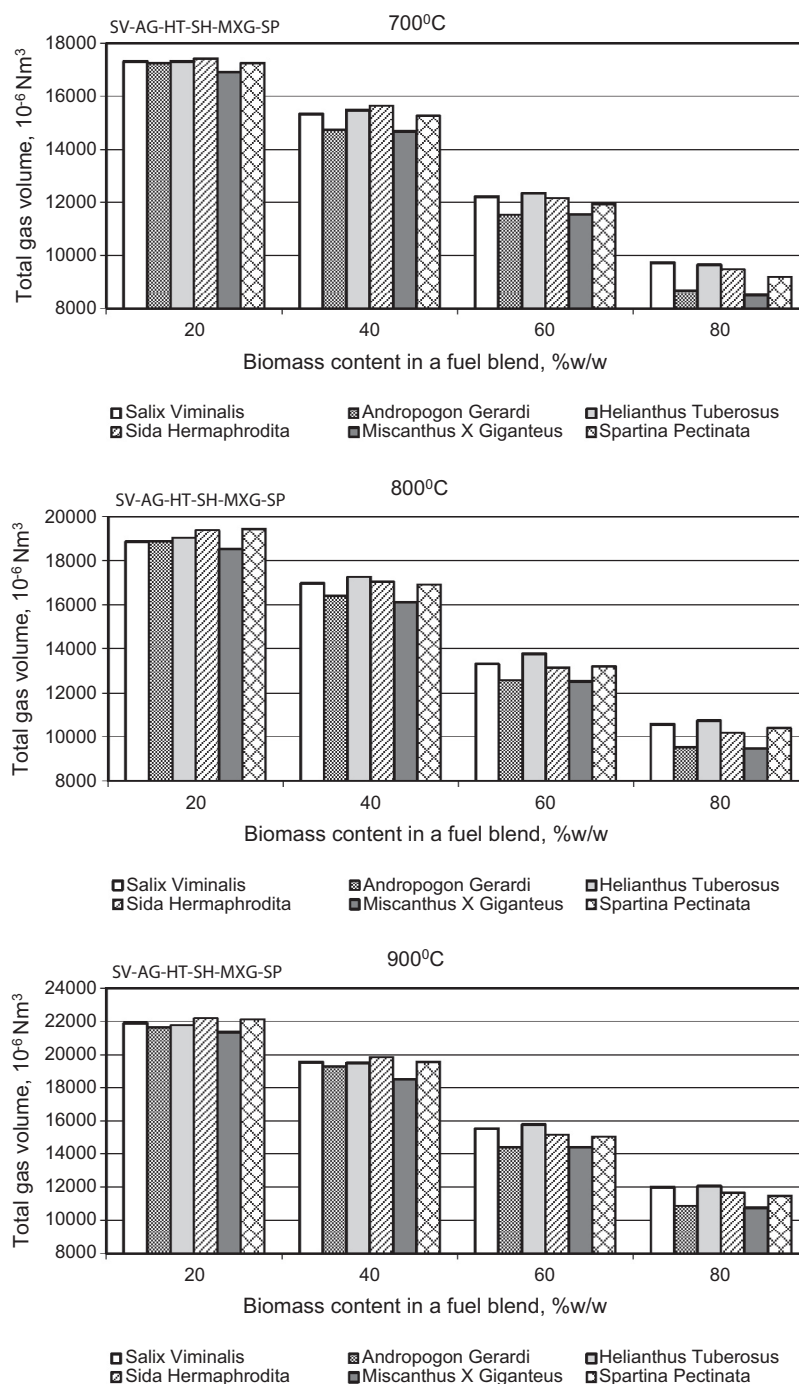


Fig. 2. Total gas volume vs biomass content in a fuel blend in steam co-gasification at 700, 800 and 900 °C.

process efficiency was studied. The major findings are presented below.

3.1. Total gas yield and carbon conversion rate vs biomass content in a fuel blend and process temperature in co-gasification experiments

3.1.1. Total gas yield

Total gas yields in the process of coal and biomass co-gasification increased with a coal content in a fuel blend at a given process temperature (see Fig. 2). The highest values were reported for 20%w/w of biomass. They varied from $16,914 \times 10^{-6} \text{ Nm}^3$ for MXG to $17,428 \times 10^{-6} \text{ Nm}^3$ for SH biomass content at 700 °C. At

800 °C the respective values were from $18,515 \times 10^{-6} \text{ Nm}^3$ for MXG to $19,372 \times 10^{-6}$ and $19,428 \times 10^{-6} \text{ Nm}^3$ for SH and SP, respectively. The total gas yields at 900 °C varied from $21,372 \times 10^{-6} \text{ Nm}^3$ for MXG to $22,172 \times 10^{-6} \text{ Nm}^3$ for SH biomass.

In the process of biomass gasification the highest gas yields were reported for biomass of the highest fixed carbon content, that is SV at 700 °C ($7192 \times 10^{-6} \text{ Nm}^3$) and HT at 800 and 900 °C (7992×10^{-6} and $8566 \times 10^{-6} \text{ Nm}^3$, respectively) (Fig. 3). Therefore it may be concluded that the discussed results of co-gasification experiments do not represent a simple additive effect (see Figs. 2 and 3) and that the synergy effects were observed in the process of co-gasification in terms of gas yield. These effects were

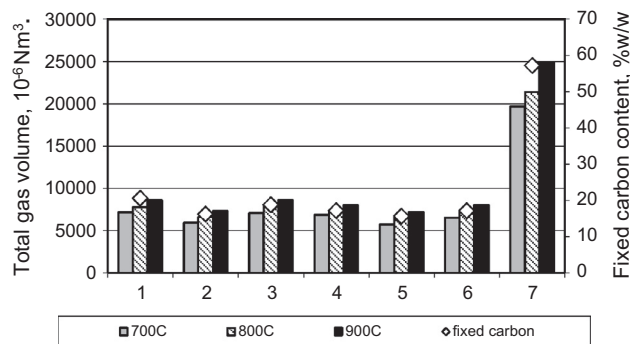


Fig. 3. Total gas volume in steam gasification of: 1 – SV, 2 – AG, 3 – HT, 4 – SH, 5 – MXG, 6 – SP and 7 – HC at 700, 800 and 900 °C.

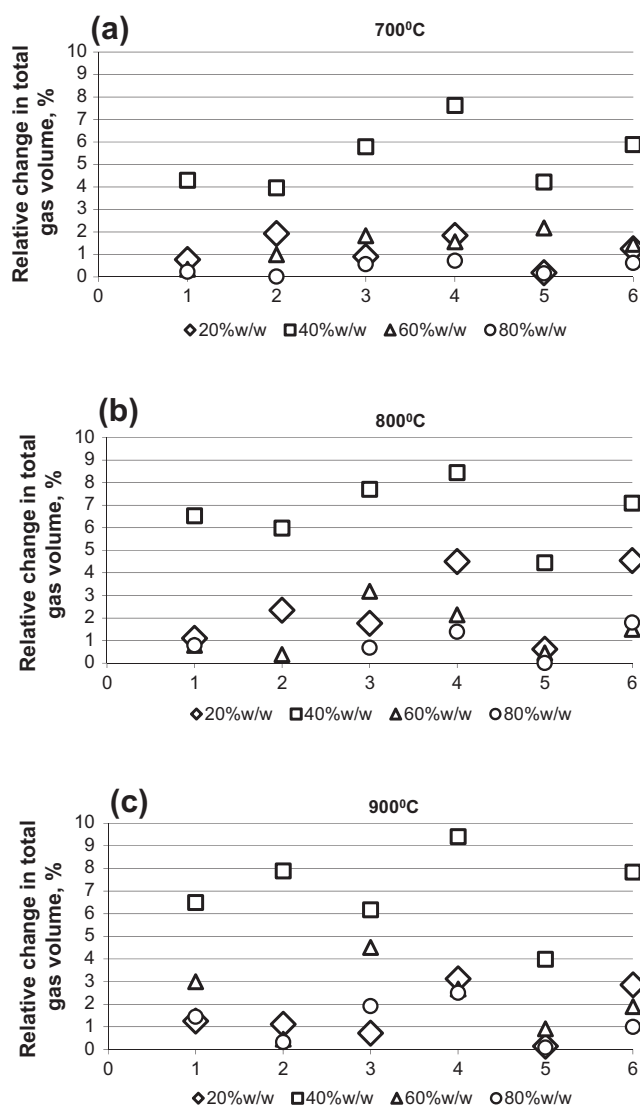


Fig. 4. Change in the total gas volume generated in co-gasification of coal and biomass of: 1 – SV, 2 – AG, 3 – HT, 4 – SH, 5 – MXG, 6 – SP and gasification of coal and biomass separately at: (a) 700, (b) 800 and (c) 900 °C.

most visible for 20%w/w of SH and SP biomass. These types of biomass were characterized by the highest potassium oxide concentration in a sample (see Table 1).

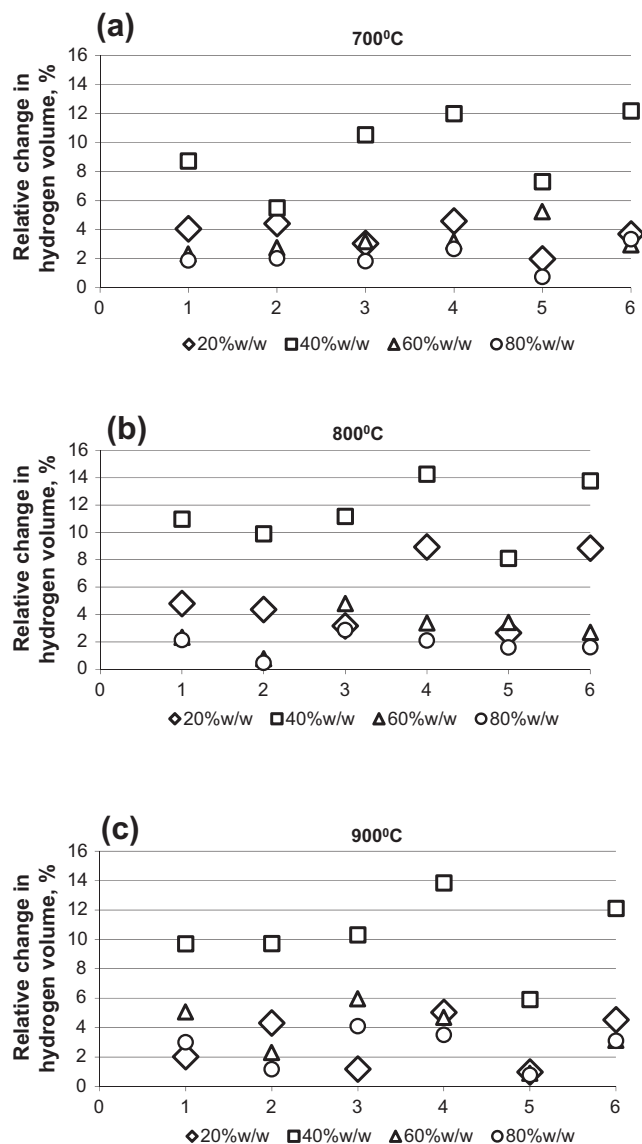


Fig. 5. Change in hydrogen volume generated in co-gasification of coal and biomass of: 1 – SV, 2 – AG, 3 – HT, 4 – SH, 5 – MXG, 6 – SP and gasification of coal and biomass separately at: (a) 700, (b) 800 and (c) 900 °C.

3.1.2. Total gas volume and hydrogen volume in co-gasification vs gasification

Increase in the total gas volume and hydrogen volume generated in the process of co-gasification was also observed when compared to the values expected based on the results of coal and biomass gasification (see Figs. 4 and 5). The maximum increase in the total gas and hydrogen volumes was observed for fuel blends of 40%w/w of biomass content, irrespective of biomass type. In previous works increase in gas yield with biomass content in co-pyrolysis and/or co-gasification was reported [20,23,32,42].

Temperature rise also resulted in the enhancement of gas production which is in line with a trend reported previously [23,32,42]. Increase in the total gas volume with a temperature increment of 100 °C (from 700 to 800 °C) varied from 7% to 15% for fuel blends of 80%w/w of SH and SP biomass content, respectively. The respective values for a temperature increase from 800 to 900 °C were from 10% for 80%w/w of SP biomass content to 17% for 40%w/w of AG biomass content. A temperature increment of 200 °C (from 700 to 900 °C) resulted in a rise in gas volume from

23% for 80w/w of SH biomass content to 31% for 40w/w AG biomass content.

3.1.3. Carbon conversion rate

Carbon conversion rate in co-gasification at 700 °C increased with increasing biomass content in a fuel blend, irrespective of biomass type, reaching the highest values in the process of biomass gasification (from 75% for SV to 83% for SH and SP). At 800 °C, a similar tendency was observed for fuel blends of SH and SP biomass. In case of the remaining energy crops, however; the maximum values were reported for 40w/w of biomass (except for MXG and AG). This trend was not observed at 900 °C. The maximum carbon conversion rates at this temperature were reported for 40w/w of SP, SH and AG (89%, 90% and 92%, respectively), 20w/w and 40w/w of SV (88%), 40w/w and 60w/w of MXG (89%) and 60w/w of HT (89%) and generally equaled or exceeded the values observed in gasification of pure biomass samples (except for 20w/w of AG and 80w/w of MXG and SP biomass).

Increase in carbon conversion rate with biomass content in a fuel blend is in line with previous observations [23,33,34,42–44].

3.2. Gas composition vs biomass content in a fuel blend and process temperature in co-gasification experiments

3.2.1. Hydrogen content

In general, the highest contents of hydrogen in gas generated in steam co-gasification process were observed for fuel blends of 40w/w of biomass content, irrespective of process temperature. The exceptions in these terms were observed for AG at 700 and 900 °C (for which the highest hydrogen concentrations were achieved with 20w/w of biomass), for HT at 800 and 900 °C (80w/w), as well as MXG at 800 °C (60w/w) and 900 °C (80w/w) (see Fig. 6). What is important, hydrogen concentrations reported in co-gasification were in general higher than the values expected based on the gasification tests of coal and biomass. The exceptions included fuel blends of AG and MXG at 800 and 900 °C and SH at 900 °C. Increase in hydrogen content in gas

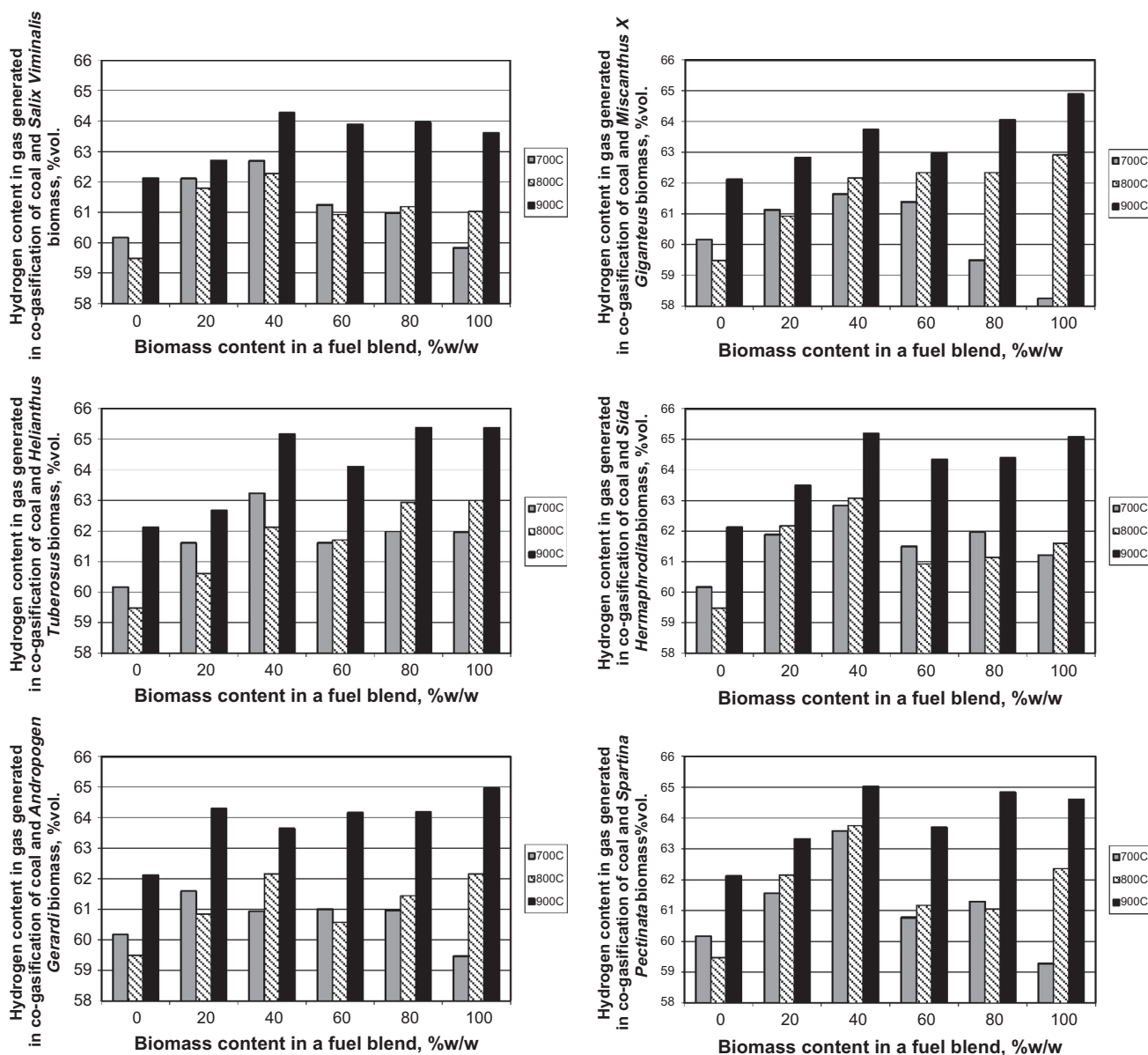


Fig. 6. Hydrogen content in gas generated in co-gasification vs biomass content in a fuel blend at 700, 800 and 900 °C.

generated in co-gasification with biomass content in a fuel blend [24,33,34,44,49] and process temperature [32,45] was previously reported. Similar tendency was also observed in coal and biomass gasification studies [46–48]. Nevertheless, the literature data on the impact of biomass content in a fuel blend on gas composition are not univocal. Decrease in hydrogen concentration in a product gas with increasing biomass content in a fuel blend was also observed [13,22,32,35,42,43,49].

3.2.2. Carbon monoxide content

The content of carbon monoxide in gas generated in steam co-gasification decreased with biomass content in a fuel blend, irrespective of biomass type, except for fuel blends of 60%w/w of biomass content. In the latter case increase or no considerable change in comparison with the concentrations reported for 40%w/w of biomass were observed. The exceptions to this tendency were reported for co-gasification of SV and MXG biomass at 900 °C, AG at 700 and 900 °C and HT and SH at 800 °C.

The highest concentrations of carbon monoxide in co-gasification were observed for 20%w/w of biomass at each process temperature considered, except for HT at 700 °C, for which the maximum carbon monoxide concentration was reported for 60%w/w of biomass. Carbon monoxide concentration increased also with process temperature and amounted to 13.38%vol., 18.42%vol., 19.49%vol., 18.71%vol., 18.25%vol. and 18.03%vol. at 900 °C for 20%w/w of SV, AG, HT, SH, MXG and SP biomass, respectively. The lowest contents of carbon monoxide in gas generated in co-gasification were observed for 80%w/w of biomass at each process temperature adopted, except for SP at 700 °C, for which the lowest concentration was reported for 40%w/w of biomass.

Concentrations of carbon monoxide observed in coal gasification (15.64%vol., 20.51%vol. and 21.66%vol. at 700, 800 and 900 °C, respectively) were higher than the values reported in biomass gasification (6.83–9.54%vol., 7.96–9.34%vol. and 8.43–10.37%vol. at 700, 800 and 900 °C, respectively) and the maximum values observed in co-gasification at respective process temperatures. On the other hand, the values reported in biomass gasification were lower than the minimum ones observed in co-gasification at a given process temperature, except for fuel blends of SV at 900, AG at 700 and HT at 800 °C. Decrease in carbon monoxide concentration in co-gasification gas with biomass content in a fuel blend was previously observed [24,43,44,49]. However, the reverse trend of increased carbon monoxide yield [34] or carbon monoxide concentration [13,32,35,42,43] with increasing biomass content in a fuel blend was also reported.

3.2.3. Carbon dioxide content

Higher biomass content in a fuel blend resulted also in carbon dioxide concentration increase in gas generated in co-gasification at a given process temperature. This tendency was reported for each type of biomass applied with some exceptions. These included fuel blends of 60%w/w of SP biomass content at 800 °C, for which the concentration of carbon dioxide was comparable to the one reported for 40%w/w of biomass, and for 20–60%w/w of HT biomass at 700 °C, 40–60%w/w of HT biomass at 900 °C and 60%w/w of SV biomass at 800 °C. The highest values of carbon dioxide were reported in biomass gasification at 700 °C (30.87%vol., 30.33%vol., 30.11%vol., 31.26%vol., 32.49%vol., 31.68%vol. for SV, AG, HT, SH, MXG and SP, respectively), except for co-gasification of SV at 900 °C, for which the maximum value was observed for 80%w/w of biomass. A rise in process temperature resulted in decrease in carbon dioxide content. The exceptions to this tendency were the concentrations of carbon dioxide in co-gasification of 40%w/w and 60%w/w of SV biomass at 800 °C, comparable with the values reported for these fuel blends at 700 and 900 °C, respectively, and the results for co-gasification of

80%w/w of HT biomass at 800 °C. The observed increase in carbon dioxide concentration with biomass content in a fuel blend is supported by the literature data [23,24,42,44]. The opposite trend, however; was also previously reported [13,35,43,49].

3.2.4. Methane dioxide content

Methane concentrations in co-gasification at 800 and 900 °C were negligible, all below 0.40%vol., with some slightly higher values reported for 40%w/w of HT biomass at 900 °C (0.68%vol.), as well as 20%w/w at 800 °C (0.47%vol.) and 20%w/w of MXG biomass at 900 °C (0.62%vol.). The highest methane concentrations were reported in co-gasification at 700 °C: 0.60–0.98%vol. for SV, 0.96–1.10%vol. for AG, 0.79–1.45%vol. for HT, 0.68–1.43%vol. for SH, 0.55–1.05%vol. for MXG and 0.96–1.38%vol. for SP biomass. Methane contents reported in co-gasification at 800 and 900 °C were lower than the respective values observed in coal (below 1.2%vol.) and biomass (below 1.5%vol.) gasification, except for co-gasification of HT and MXG biomass at 900 °C. In co-gasification of 20–80%w/w of SH and SP biomass at 800 and 900 °C methane concentrations were below the detection level.

3.3. Co-gasification process efficiency

Co-gasification process efficiency increased with increasing coal content in a fuel blend and process temperature. The maximum values at a given process temperature were reported for 20%w/w of biomass and amounted to: 60% for AG and SH at 700 °C, 68% for HT, SH and SP at 800 °C and 81% for AG, HT and SH at 900 °C. The lowest values of process efficiency were observed in co-gasification of 20%w/w of SV (41%, 45% and 51%) and MXG biomass (40%, 45% and 54%) at 700, 800 and 900 °C, respectively. The values reported in coal gasification (63%, 71% and 86%, at 700, 800 and 900 °C, respectively) exceeded the ones observed in co-gasification. This effect may be attributed to higher content of combustible gas components, in particularly carbon monoxide, and higher volumes of gas generated in coal gasification, when compared to the respective values reported in co-gasification.

Increase in process efficiency with process temperature rise from 700 to 900 °C was also reported. It amounted to: 26–28%, 27–36%, 30–36%, 30–38%, 30–41% and 34–37% in co-gasification of SV, SH, SP, HT, AG and MXG biomass, respectively. The modest increase in co-gasification process efficiency with increasing temperature was observed for 80%w/w of biomass. The most significant one was observed for 40%w/w of SV, AG, MXG and SP biomass and 60%w/w of HT and 20%w/w of SH biomass.

The maximum increase in process efficiency reported for AG (40%w/w) and HT (60%w/w) was higher, and in co-gasification of fuel blends of MXG and SP – comparable to the values reported in coal gasification. In biomass gasification the highest increase in process efficiency was, however; observed for HT biomass (of relatively low calorific value), and the lowest for MXG, for which the lowest volumes of gas were reported. The highest values reported for HT, AG, SH and SP prove therefore the synergy effect, most evident for fuel blends of biomass types of the highest content of potassium, sodium, calcium and manganese oxides (see Table 1).

Fuel blends of SV and MXG biomass were characterized by the lowest co-gasification process efficiency. This may be attributed to the lowest gas volumes and hydrogen concentrations reported in co-gasification of MXG on the one hand, and the lowest carbon monoxide content in co-gasification product gas reported for SV on the other. These biomass types were also characterized by the lowest ash content (see Table 1). Furthermore, MXG biomass contained the lowest amounts of calcium, manganese, sodium and potassium oxides among all the biomass types tested. Concentrations of these oxides in SV biomass were lower than in HT and

SH biomass samples, but comparable with the amount of calcium oxide and potassium oxide in AG biomass sample and manganese oxide in SP biomass sample. Sodium oxide content in SV biomass sample was the lowest and similar to the value reported for MXG. The observed trend of rise in process efficiency with co-gasification and gasification process temperature was previously reported [32,45–48,50]. With increasing biomass content in a fuel blend increases in process efficiency [13,32–35,43] and reactivity [20,21,23,37,51,52] were also observed.

The ambiguity of the data available on the effect of biomass content in a fuel blend on product gas composition, yield of particular gas components and synergy effects in co-pyrolysis or co-gasification presented in Section 3 is inherently combined with the differences in operating conditions adopted. These include type of fuel blends, reactor configurations, operating parameters, determining among the others the residence time of fuel/chars in reaction zone, reaction rate as well as contact between fuel particles and gasification agent or volatile by-products of the process.

4. Conclusions

1. The results of the experimental study presented in the paper proved the synergy effects in co-gasification of coal and biomass of selected energy crops under operating conditions adopted in terms of increase in the total gas and hydrogen yields, when compared to the values expected based on the results of coal and biomass gasification. A correlation between ash composition (metal oxides contents) and the observed synergy effects was also noticed. Based on the results presented it may be concluded that the effects observed may be related to the catalytic activity of some of the ash components, e.g. alkali and alkali earth metals, which, however; need further detailed studies to be fully confirmed.
2. The optimal values of operating parameters in steam co-gasification to hydrogen-rich gas in the selected range of variables (process temperature, types of fuels tested and biomass content in a fuel blend) and in the fixed-bed reactor configuration were determined: process temperature of 900 °C, 40%w/w biomass content in a fuel blend and SH, SP and HT as energy crops biomass.
3. The following general trends were observed in the experiments performed:
 - 3.1 Increase in the total gas and hydrogen yields, process efficiency and carbon conversion rate with increasing co-gasification process temperature.
 - 3.2 Increase in the total gas and hydrogen yields in comparison with the values expected based on the results of coal and biomass gasification process under similar operating conditions. The highest values of the total gas volume and hydrogen volume, higher than the values expected based on relevant gasification tests (synergy effect) were reported for fuel blends of 20%w/w of biomass content, the maximum for SH and SP biomass. The highest increases in the total gas and hydrogen volume in co-gasification, when compared to the results of gasification, were reported for 40%w/w of biomass.
 - 3.3 Increase in hydrogen content and decrease in carbon dioxide content in co-gasification product gas with a rise in process temperature.
 - 3.4 Increase in carbon dioxide and decrease in carbon monoxide concentrations in co-gasification product gas with increasing biomass content in a fuel blend. The maximum concentrations of hydrogen in co-gasification product gas were observed for 40%w/w of biomass, irrespective of biomass type, at 700 °C, and most of the biomass types at 800

and 900 °C (synergy effect). The highest hydrogen contents in product gas, at respective process temperature adopted, were reported for fuel blends of HT, SH and SP biomass.

- 3.5 Methane content in co-gasification product gas was negligible: max 1.45%vol. at 700 °C and in general below 0.40%vol. at 800 and 900 °C, and lower than in coal and biomass gasification process.
- 3.6 Increase in process efficiency with decreasing biomass content in a fuel blend was observed. The highest values of process efficiency in co-gasification were reported for 20%w/w of biomass, with maximum for HT, AG, SH and SP biomass.
4. The process of coal and biomass steam co-gasification may be considered as an alternative to coal or biomass gasification, offering fuel supplies security, large scale of operation, and lower CO₂ emission, resulting from utilization of renewables. It may also give the advantage of potential utilization of catalytic activity of some of biomass ash components, which may increase the efficiency of hydrogen-rich gas production in co-gasification, as a cost-effective alternative to conventional catalysts applied in coal and biomass gasification.

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